



NON-IMAGING, FOCUSING HELIOSTAT

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Abstract—A non-imaging focusing heliostat for effective use of thermal solar energy is proposed. The heliostat consists of a number of grouped slave mirrors, which are able to move according to a proposed formula to eliminate the first order aberration. The master mirror tracks the sun by a proposed rotation-elevation mode to project solar rays together with the rest of slave mirrors into a fixed target. The merit of this design is that it may benefit the use of solar energy in high temperature applications by allowing a single stage collector to replace a conventional double stage structure; it may also benefit high concentration applications, e.g., solar powered Stirling engines, solar pumped lasers, etc. The feasibility and a reliability test of the proposed method by a prototype heliostat in the University of Technology, Malaysia is reported. © 2001 Published by Elsevier Science Ltd.

1. INTRODUCTION

Two types of solar collectors are used in thermal energy applications: moving target type and fixed target type. The popular devices for moving target type include parabolic dish, parabolic trough, spherical bowl (or so-called Fixed Mirror Distributed Focus) etc. (Stine and Harrigan, 1985). The fixed target type which involves the use of a heliostat includes the central power tower (Stine and Harrigan, 1985; Winter *et al.*, 1991a), the solar furnace (Riskiev and Suleimanov, 1991; Lewandowski *et al.*, 1991) etc. The moving target devices are usually used for smaller scale and lower power applications comparing to that of fixed target solar collectors. In the case of the central power tower, if the heliostat consists of a plane reflective surface, inevitably, the images at the target have relatively large dimensions, limiting the achievable concentration. Even if concave mirrors are used, the large aperture is only moderately reduced (Baranov, 1980), and cannot be directly used to apply to the small receiving area of some thermo-mechanical convectors, e.g., the heat part of a Stirling engine. Only the solar

furnace, employing two-stage reflection through plane heliostats directing parallel beams into a huge parabolic mirror, can provide very high concentration (greater than 5000) and power to focus the solar rays at small area. However, a two-stage solar furnace typically involves high cost and long engineering time, particularly for the precise optical alignments, hindering the popular use of the solar furnace.

This paper proposes a new design to achieve high concentration and power while keeping the fabrication cost relatively low. Our modification from the conventional heliostat comprises two steps: firstly, we designed the slave mirrors, such that they are able to be controlled to realize a variable focusing; secondly, we changed the usual azimuth-elevation tracking mode (Alpert *et al.*, 1991; Murphy, 1986) replacing it with an rotation-elevation mode.

These modifications have to take place concurrently (Chen and Bligh, 1997). It would be a trivial idea to realize sunlight focusing by manipulating each slave element mirror if the traditional sun tracking method is employed. This will be very costly. For example, if there are M rows and N columns of element mirrors on the heliostat, because each mirror will require two degrees of freedom, $2 \times (M \times N)$ controlling devices have to be used. That is hardly practical. Therefore, a different tracking method has to be explored to make the construction of the heliostat with many

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element mirrors cost effective while maintaining a precise sun tracking. In our new design, the frame of the heliostat, instead of moving the facet along the azimuth direction, moves the facet along the rotation direction and then along elevation. The rotation-elevation mode of tracking is not so popular in heliostat control, therefore no detailed analysis has been published hitherto. However, it has been mentioned by some authors in a previous publication (Schubnell and Ries, 1990; Zaibel *et al.*, 1995). Consequently, it has the advantage that the elevation axis is maintained perpendicular to the plane containing the mirror normal, the sun and the target, i.e., in the plane of reflection. In our design, by introducing a new rotation axis to the heliostat frame, the slave mirrors of the same column or the same row can be arranged to share the same driving device. Thus, the number of controlling components can be significantly reduced to $M + N$. Furthermore, as we will explain, in contrast with the alignment procedure of the conventional two-stage solar reflector system, which is rather complicated and costly, in our design the alignment procedure can be simplified, thus, the engineering time can be greatly shortened.

The working principle of the heliostat will be described in two parts: primary tracking of heliostat and secondary tracking of slave mirrors.

2. THE PRINCIPLE OF NON-IMAGING FOCUSING HELIOSTAT

In our design of the non-imaging focusing heliostat, mirrors are arranged in rows and columns. The central column is maintained in the optical plane by rotating the frame. The master mirror is fixed at the centre with slave mirrors surrounding it, they share the same frame but the slave mirrors have two extra degrees of freedoms to move about their pivot points. To focus all the mirror images into one fixed target, each slave mirror is angularly moved about its pivot point to reflect sunrays onto the same target as the master mirror. The result at the target is the total combination of individual mirror images. As the sunlight is not coherent, the result is the algebra sum of the energy of the beams without a specific optical image.

2.1. Primary tracking

The purpose of primary tracking is to target the solar image of the master mirror into a stationary receiver. Then, this image acts as a reference for secondary tracking where all the slave mirror images will be projected on it. In Fig. 1(a), we define $\underline{ON}$ as the vector normal to the reflector surface; $\underline{OS}$ as the vector that points to the sun; $\underline{OT}$ as the vector that points to a fixed target; $\underline{QT}$ as the vector that points to a fixed target. Fig.

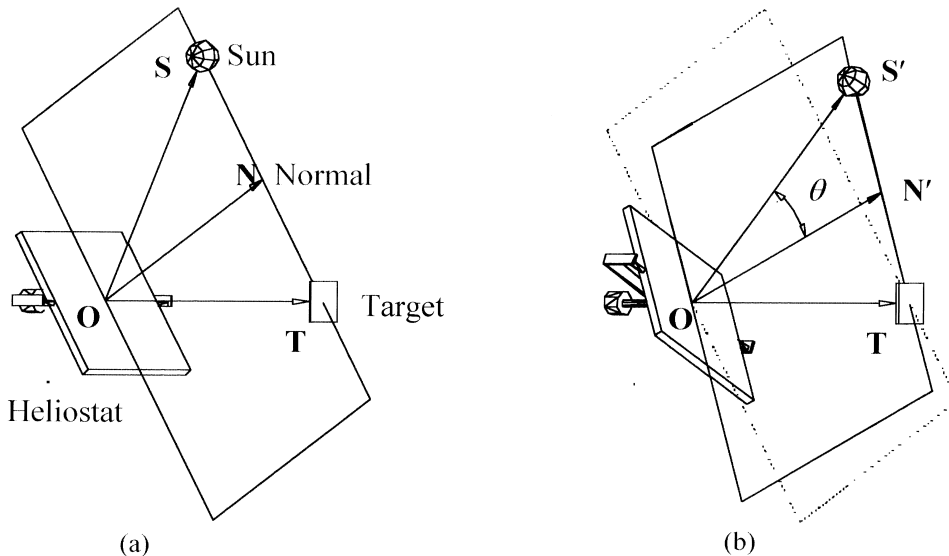


Fig. 1. Rotation modes of non-imaging focusing heliostat. (a) $\underline{ON}$ is defined as the normal vector of the heliostat surface; $\underline{OS}$ is the vector that points to the sun; $\underline{OT}$ is the vector that points to a fixed target. (b) The rotation of the plane of reflection, that plane which contains the three vectors ($\underline{OS}$, $\underline{ON}$ and $\underline{OT}$), during primary tracking. In the new reflection plane, the vector $\underline{OS}$ points to the new position of the sun and the vector $\underline{ON'}$ is the reflector normal of the new orientation so that the sunlight is still reflected towards the target.

1(b) shows the rotation of the plane of reflection, that plane which contains the three vectors ($\underline{QS}$, $\underline{QN}$ and $\underline{QT}$), during primary tracking. In Fig. 1(b), the vector $\underline{QS'}$ points to the new position of the sun and the vector $\underline{QN'}$ is the reflector normal of the new orientation so that the sunlight is still reflected towards the target. The tracking movement can be studied by two independent components (Fig. 2):

2.1.1. Rotation movement. The heliostat has to rotate about the TT' axis so that the plane of reflection can follow the rotation of the vector $\underline{QS}$. Therefore, as the sun moves through the sky from the morning to solar noon, the plane will rotate starting from horizontal and turning to vertical. The angular movement about this rotation axis is denoted as ρ .

2.1.2. Elevation movement. The rotation of the heliostat about the FF' axis (perpendicular to the plane) will adjust the reflector normal position within the plane until it bisects the angle between $\underline{QS}$ and $\underline{QT}$. As a result, the sunlight will be reflected onto the target. This angular movement depends on the incidence angle of the sun relative to the heliostat surface normal and it is denoted as θ .

The formulas for ρ and θ can be derived by transformation of two different coordinate sys-

tems: one attached to the centre of the earth and the other attached to the local heliostat.

In Fig. 3(a), by defining a coordinate system with the origin, C, set at the centre of the earth, the CM axis is a line from the origin to the intersection point between the equator and the meridian of the observer at Q. The CE (east) axis in the equatorial plane is perpendicular to CM axis. The third orthogonal axis, CP is the rotation axis of the earth. Vector $\underline{CS}$ pointing to the sun can be described in terms of its direction cosines, S_m , S_e and S_p to the CM, CE, and CP axes respectively. Given the direction cosines of $\underline{CS}$ in terms of declination angle (δ) and hour angle (ω), we have a set of coordinates in matrix form

$$\mathbf{S} = \begin{bmatrix} S_m \\ S_e \\ S_p \end{bmatrix} = \begin{bmatrix} \cos \delta \cos \omega \\ -\cos \delta \sin \omega \\ \sin \delta \end{bmatrix} \quad (1)$$

Fig. 3(b) illustrates another coordinate system, which is attached to the local heliostat. The local heliostat reference frame is referred to only when the heliostat frame is oriented in such a way that the normal of the master mirror becomes parallel with the rotation axis. The origin of the coordinate system is defined at the centre of the master mirror and is denoted as O. The OR axis is parallel with the array of mirrors arranged in the

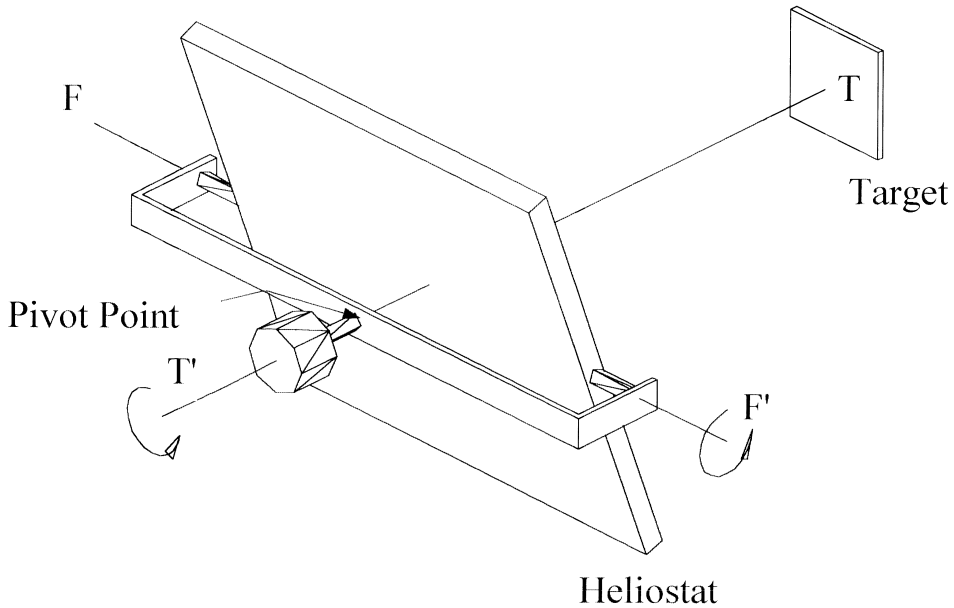


Fig. 2. Diagram to show the mounting of non-imaging focusing heliostat. The heliostat has two tracking axes that are perpendicular to each other, as does the conventional mount. First rotational axis is pointing toward the target and it is indicated by TT' axis. The second axis, elevation axis is attached parallel to the reflector and it is shown as FF' axis.

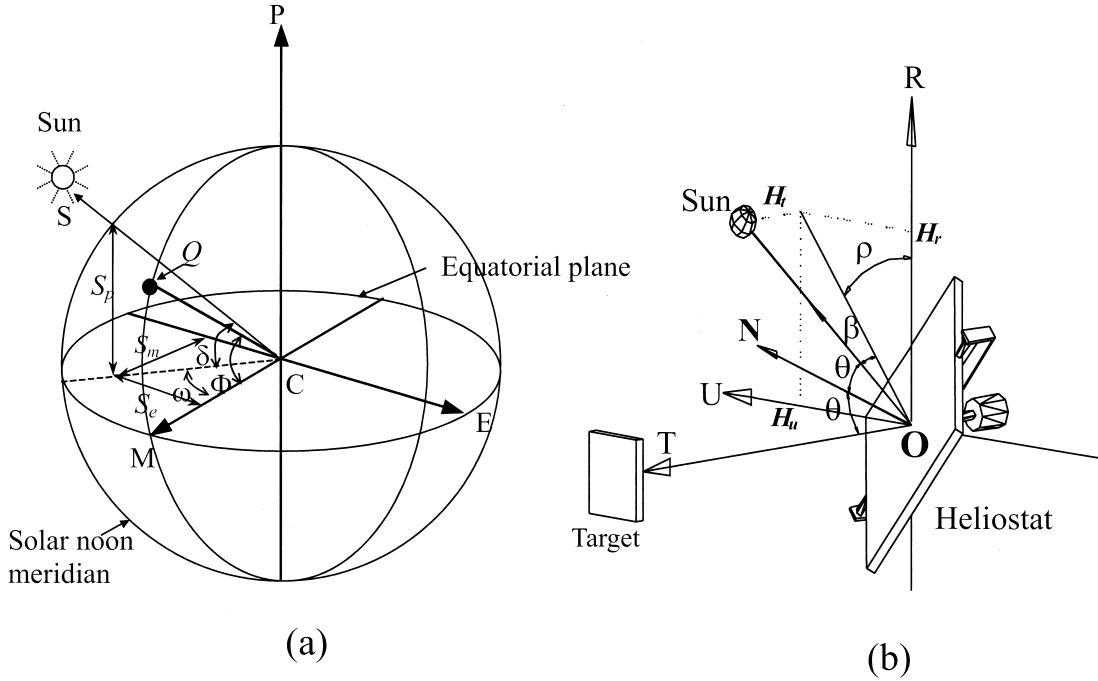


Fig. 3. (a) Coordinate system attached to earth reference frame. The vector $\underline{CS}$ that points towards the sun can be described in terms of hour angle ω and the declination angle δ . The observer Q is located at the latitude Φ . By defining a coordinate system with the origin, C , set at the centre of the earth, the CM axis is a line from the origin to the intersection point between the equator and the meridian of the observer at Q . The CE (east) axis in the equatorial plane is perpendicular to CM axis. The third orthogonal axis, CP is the rotation axis of the earth. (b) Coordinate system attached to the local heliostat reference frame. The vector $\underline{OS}$ is in the function of the angle β and the angle ρ . The relationship between the incidence angle θ and the angle β is $\pi/2 = 2\theta + \beta$. The local heliostat reference frame is referred to only when the heliostat frame is oriented in such a way that the normal of master mirror becomes parallel with the rotation axis. The origin of the coordinate system is defined at the centre of the master mirror and is denoted as O . The OR axis is parallel with the array of mirrors arranged in the vertical direction of the heliostat frame. The second axis, OU axis is parallel with the array of mirrors arranged in the horizontal direction. The third orthogonal axis, OT axis is a line pointing out from the origin towards the target direction.

vertical direction of the heliostat frame. The second axis, OU is parallel with the array of mirrors arranged in the horizontal direction. The third orthogonal axis, OT is a line pointing out from the origin towards the target. Similar to the case of $\underline{CS}$, vector $\underline{OS}$ pointing to the sun can be described in terms of its direction cosines, H_r , H_u and H_t to the OR , OU , and OT axes respectively. In daily sun tracking, the elevation axis (FF') is rotated about the OT axis from the morning to the evening, but the OR and OU axes remain static all the time. The angle between the OU axis and the FF' axis is ρ and these two axes coincides with each other at solar noon.

Given the direction cosines of $\underline{OS}$ in terms of the angles β and ρ , we have a set of coordinates in matrix form

$$\mathbf{H} = \begin{bmatrix} H_r \\ H_u \\ H_t \end{bmatrix} = \begin{bmatrix} \cos \beta \cos \rho \\ -\cos \beta \sin \rho \\ \sin \beta \end{bmatrix} \quad (2)$$

where β is the angle between the vector $\underline{OS}$ and

its projection on the plane that contains the OR and OU axes. From the law of reflection, Figs. 1 and 3 show that θ is obviously:

$$\theta = \frac{1}{2} \left(\frac{\pi}{2} - \beta \right) \quad (3)$$

The new set of coordinates, $\mathbf{H}$, can be interrelated to the earth frame based coordinates, $\mathbf{S}$, by three successive rotation transformations.

The first transformation is effected by a rotation about the CE axis through the latitude angle Φ (see Fig. 3(a)). In matrix notation, it takes the form

$$\Phi = \begin{bmatrix} \cos \Phi & 0 & \sin \Phi \\ 0 & 1 & 0 \\ -\sin \Phi & 0 & \cos \Phi \end{bmatrix} \quad (4)$$

In the non-imaging focusing heliostat, the rotation axis (TT' axis) has to be aligned pointing towards the target and the elevation axis (FF' axis) is perpendicular to the first axis and attached parallel to the reflector. If more than one heliostat share a

common target, each heliostat has its own orientation of the rotation axis relative to the earth surface. Taking into account of the orientation angles of the rotation axis, which are facing angle ϕ and target angle λ , it is necessary to have two transformations. The facing angle, ϕ , is the rotation angle about the Zenith made by the rotation axis (OT) when it rotates from the direction pointing towards north to the direction pointing towards a fixed target (assuming that the fixed target and central point of master mirror are at the same horizontal level). Hence, $\phi = 0^\circ$ if the heliostat is placed due south of the target; $\phi = 90^\circ$ if the heliostat is located due west of the target. The transformation matrix for the angle ϕ about the Zenith is

$$\phi = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi & -\sin \phi \\ 0 & \sin \phi & \cos \phi \end{bmatrix} \quad (5)$$

In general, the central point of the master mirror is not at the same horizontal level with the focusing target. Therefore, a rotation transformation through the angle λ about OU axis is required. $\lambda = 0^\circ$ means that the central point of the master mirror is at the same horizontal level as the target; $\lambda = 10^\circ$ means that the OT axis is at the position 10° clockwise from the horizontal line i.e., the target is below the heliostat. The transformation matrix is then

$$\lambda = \begin{bmatrix} \cos \lambda & 0 & \sin \lambda \\ 0 & 1 & 0 \\ -\sin \lambda & 0 & \cos \lambda \end{bmatrix} \quad (6)$$

Finally, $\mathbf{H}$ is the product of λ , ϕ , Φ and $\mathbf{S}$ as follows:

$$\mathbf{H} = \lambda \phi \Phi \mathbf{S} \quad (7)$$

$$\begin{aligned} \begin{bmatrix} \cos \beta \cos \rho \\ -\cos \beta \sin \rho \\ \sin \beta \end{bmatrix} &= \begin{bmatrix} \cos \lambda & 0 & \sin \lambda \\ 0 & 1 & 0 \\ -\sin \lambda & 0 & \cos \lambda \end{bmatrix} \\ &\times \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi & -\sin \phi \\ 0 & \sin \phi & \cos \phi \end{bmatrix} \begin{bmatrix} \cos \Phi & 0 & \sin \Phi \\ 0 & 1 & 0 \\ -\sin \Phi & 0 & \cos \Phi \end{bmatrix} \\ &\times \begin{bmatrix} \cos \delta \cos \omega \\ -\cos \delta \sin \omega \\ \sin \delta \end{bmatrix} \end{aligned} \quad (8)$$

From the solutions of the matrix, we obtain β and ρ as

$$\begin{aligned} \beta &= \text{ArcSin} \\ &\left\{ \begin{aligned} &-\cos \delta \cos \omega (\sin \lambda \cos \Phi + \cos \lambda \cos \phi \sin \Phi) - \cos \delta \sin \omega \cos \lambda \sin \phi \\ &+ \sin \delta (\cos \lambda \cos \phi \cos \Phi - \sin \Phi \sin \lambda) \end{aligned} \right\} \end{aligned} \quad (9)$$

$$\rho = \text{ArcSin}$$

$$\left\{ \frac{-\cos \delta \cos \omega \sin \phi \sin \Phi + \cos \delta \sin \omega \cos \phi + \sin \delta \sin \phi \cos \Phi}{\cos \beta} \right\} \quad (10)$$

Substituting the Eq. (9) into Eq. (3), we have

$$\begin{aligned} \theta &= \frac{\pi}{4} - \frac{1}{2} \text{ArcSin} \\ &\left\{ \begin{aligned} &-\cos \delta \cos \omega (\sin \lambda \cos \Phi + \cos \lambda \cos \phi \sin \Phi) - \cos \delta \sin \omega \cos \lambda \sin \phi \\ &+ \sin \delta (\cos \lambda \cos \phi \cos \Phi - \sin \Phi \sin \lambda) \end{aligned} \right\} \end{aligned} \quad (11)$$

Eqs. (10) and (11) represent a rotation-elevation tracking mode. We used this mode to perform sun tracking by using a prototype and it has been proven successfully. However, with the movement of the central master mirror, the images of the slave mirrors will be inevitably aberrant. To achieve a high concentration, the slave mirrors need to be adjusted accordingly to overcome this aberration. This adjustment is rather minor, particularly if the target is far away from the heliostat. The principle of this secondary order tracking is illustrated in the following section.

2.2. Secondary tracking

The new tracking mode encourages the arrangement of the slave mirrors to be grouped into rows and columns, as under this mode the mirrors in the same row or column will have the same movement. Fig. 4 shows the side view of a 25-mirror heliostat with P representing the heliostat frame and the central row (row 3) contains master mirror. The elevation axis FF' lies outside the page and the rotation axis, OT points towards the target. Slave mirrors of row 1, 2, 4 and 5 are attached to the heliostat frame in such a way that they can turn about their own pivot point P_1 , P_2 , P_4 and P_5 respectively. To superpose four rows of solar images onto the central image, each row of slave mirrors has to be rotated through an angle, σ ,

$$\sigma = \frac{1}{2} \text{ArcTan} \left(\frac{H \cos \theta}{H \sin \theta + L} \right) \quad (12)$$

where L is the distance between the central point of the master mirror at O and the target point at T (refer to Fig. 4); H (positive for rows above the master mirror and negative for rows below the master mirror) is the distance from the centre of the master row to the centre of the row where the corresponding slave mirror is located.

Similarly, to overlap four columns of slave images onto the central master image, each column has to be moved through an angle,

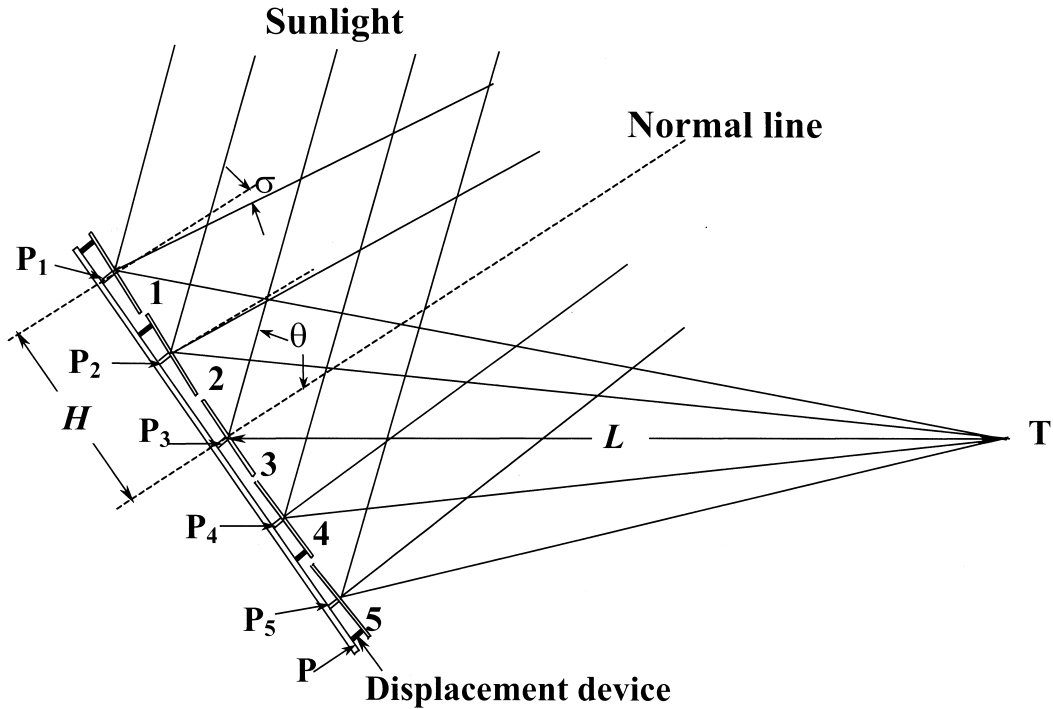


Fig. 4. The side view of a 25-mirror heliostat with P representing the heliostat frame. The central row (row 3) contains master mirror. Slave mirrors of row 1, 2, 4 and 5 are attached to the heliostat frame in such a way that they can be turned about their own pivot point P_1 , P_2 , P_4 and P_5 respectively.

$$\gamma = \frac{1}{2} \text{ArcTan} \left(\frac{H}{L \cos \theta} \right) \quad (13)$$

where the definition of L and θ remain the same while H is the distance between the centre of the master column and the centre of the column where the corresponding slave mirror is located.

Figs. 5 and 6 give some examples of the angular movements for $L=40$ m and different values of H as 0.4 m, 0.8 m, 1.2 m and 1.6 m. In Fig. 5, we can see that the angle σ is rather small with maximum value less than 1.2° . For angles of incidence θ less than 80° , the angle γ is smaller than 7° (see Fig. 6). Because the angles σ and γ are small, the angular movements can be approximated to linear movement which benefits the design of heliostat because low cost driving devices can be used.

In the above, we described a variable focusing method to overcome the image aberration. A natural question then is: how much can we eliminate the effects. This is important, as any residual aberration left will affect the size of the focused image. We have used a computer program to conduct a lengthy study of this problem. It has shown that although the above method can indeed eliminate most of the aberration, some residual effects still exist particularly when the distance

between heliostat and target is relatively short. The detailed study will be submitted for publication soon. But it is necessary to point out here that the residual aberration is reasonably small and can be neglected in most applications. In the case of our first generation prototype as will be discussed in next section, for $H=1$ m, if the target is 20 m away from the heliostat, the residual aberration on the target is 1.25 cm, if the distance is 5 m, it is 5 cm. The larger the ratio of L to H , the smaller the effect will be. This is so because Eqs. (12) and (13) will make more effective correction to the residual aberration at longer distance. Of course, at longer distance, the control precision and resolution of the correction movement of the slave mirrors have to be higher. Our theoretical study has been well proven by the observation using the prototype heliostat.

In addition to the residual aberration, the focusing area of the heliostat is also limited by the image of the solar disc. Because the sun presents a finite object which has an angular diameter 9.4 mrad at the earth, the minimum spot diameter of a perfectly focused solar image is approximated to the focal length of the reflector multiplied by 9.4 mrad (Winter *et al.*, 1991b). If a flat circular mirror reflects solar radiation to a target, the solar image at the target will have a diameter

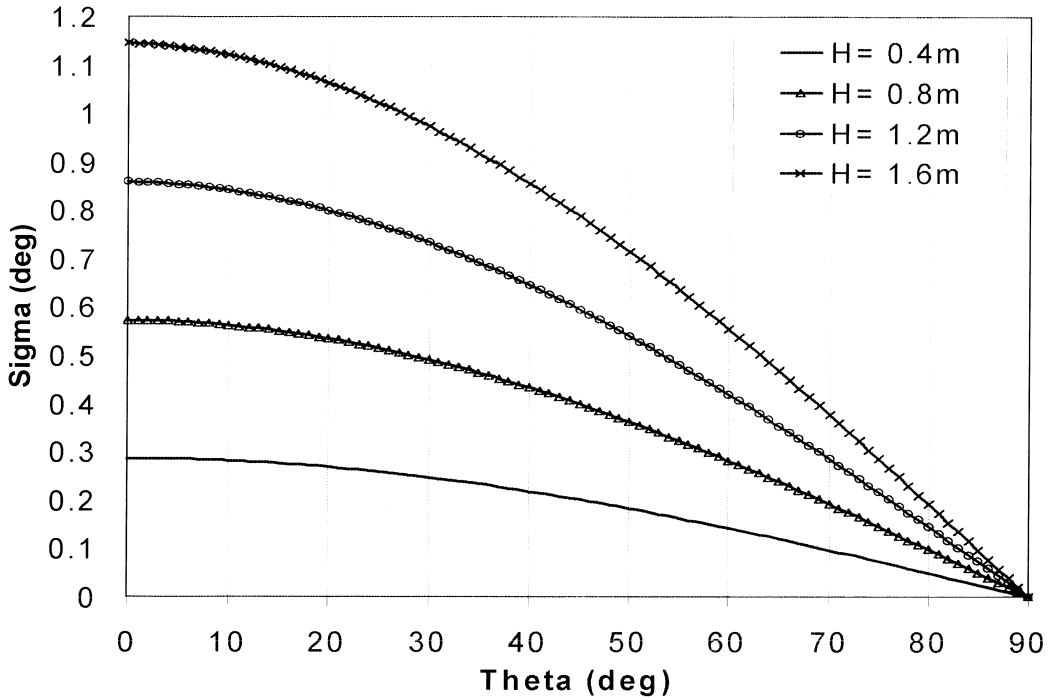


Fig. 5. The angular movement σ versus the incidence angle θ of the sun for $L = 40$ m and different value of H as 0.4 m, 0.8 m, 1.2 m, and 1.6 m. In the graph, σ is rather small with maximum value less than 1.2° .

of the mirror itself plus the diameter of the solar disc image (the cosine effect is ignored). For instance, the image of a flat mirror with diameter

40 cm reflected to a target 20 m away has a size of 59 cm diameter. However the size of the image can be made smaller when the mirror is concave.

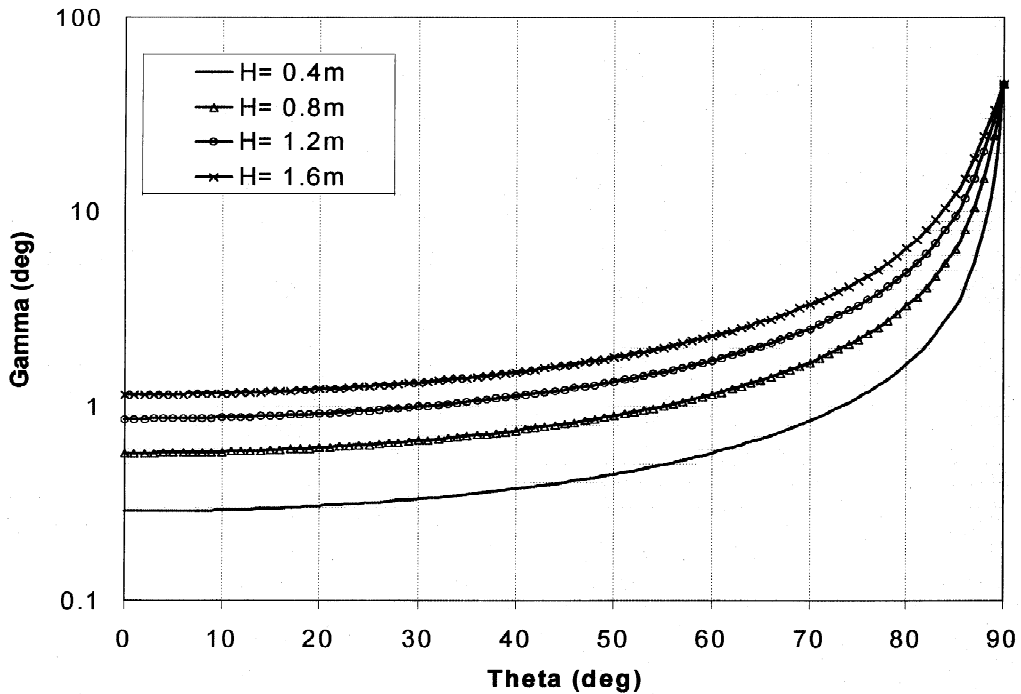


Fig. 6. The angular movement γ versus the incidence angle of the sun for $L = 40$ m and different value of H as 0.4 m, 0.8 m, 1.2 m, and 1.6 m. For θ less than 80° , γ is smaller than 7° .

The minimum spot size of the concave mirror is essentially limited by two main factors: astigmatism and the image of the solar disc. For each perfectly focused slave mirror image, the minimum spot size of the solar disc image increases with the target distance. Due to this fact, it is easy to understand that there will be a discriminating target distance where the spot size of the solar disc image starts to surpass the mirror size. In the case of our heliostat, it is convenient to use square mirrors. For the use of 40 cm $\times$ 40 cm element mirrors, the discriminating distance at which the concentration equals to the number of mirrors is 42 m. The limiting factors for the achievable concentration will be discussed in detail in our next paper.

3. PROTOTYPE OF NON-IMAGING FOCUSING HELIOSTAT IN UTM

To test the feasibility of the new architecture, a prototype non-imaging focusing heliostat with 25 mirrors has been constructed in the campus of University of Technology Malaysia (UTM). Mirrors made of glass with dimension of 40 cm $\times$ 40 cm each are arranged into five rows and five columns to form a total reflective area of 4 m². The entire body consists of one master mirror and 24 slave mirrors. The heliostat frame can be rotated around elevation and rotation axes via two main stepper motors and associated gears to achieve sun track-

ing. Eight additional small motors drive four columns and four rows where the slave mirrors are attached. The target is set due north of the heliostat. The distance between the target and heliostat is variable.

A Pentium based PC is used to control both the primary tracking and secondary tracking according to solar time, local latitude and the orientation angles of the heliostat's rotation axis relative to the earth surface. The secondary tracking is purely open loop. The primary tracking is structurally closed-loop where two optical encoders are used to provide an absolute reference and precise counting to prevent losing steps due to environmental effects, e.g. wind. In this context, two optical encoders with a precision of 5000 counts/rev are attached on the shafts of the rotation and elevation axes to count the actual movement. Fig. 7 shows a prototype heliostat that has successfully focused 25 images into one fixed target and maintained it throughout the day. The prototype has been used for the testing run of a Stirling engine and solar pumped laser. The details of the work will be reported later. The heliostat has undergone more than 400 solar days' test since it was installed in 1997.

Unlike a two-stage solar furnace, optical alignment will not be complicated and time consuming. However, in order to achieve good precision, a certain method of alignment has to be employed as briefly described in the following.

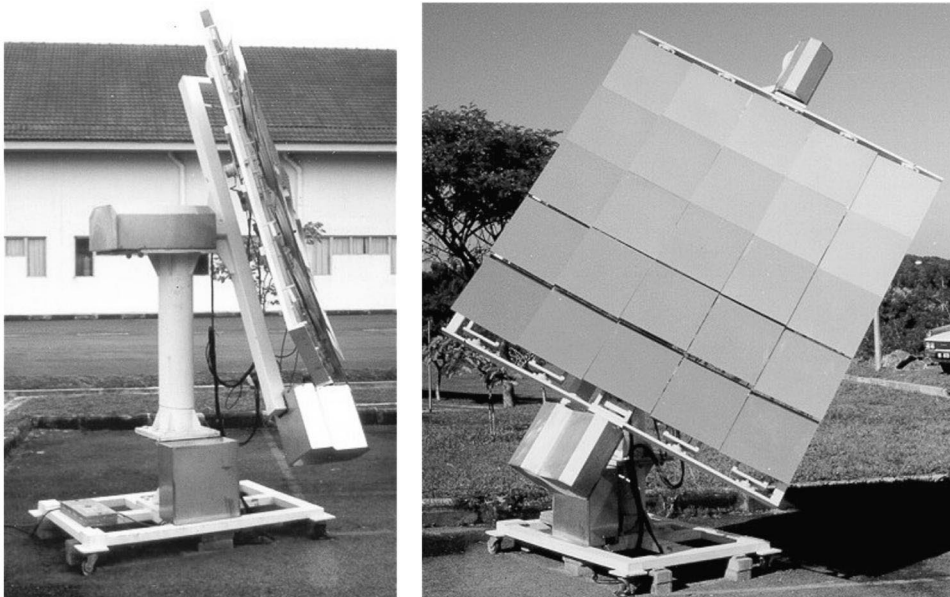


Fig. 7. The prototype of non-imaging heliostat that has successfully focused 25 images into one fixed target and maintained it throughout the day. In UTM, the heliostat has undergone more than 400 solar days' test since it was installed in 1997. (right – front view, left – side view).

In our new scheme of design, the precision of the optical alignment of the rotation axis with the target is important. This is particularly so when more than one heliostat is used for a common target. All the rotation shafts must be well in line with the target. In our prototype, although a single heliostat is used, for the purpose of testing, an alignment structure was constructed. The structure is illustrated schematically in Fig. 8 where a laser tube or a telescope can be employed along the central axis of the shaft, which is mounted on a platform capable of two-degree-of-freedom adjustment. The laser or telescope is used to optically align the target by maneuvering the platform. After the alignment is completed, locking bolts are used to tighten the adjustable parts. Practical experience has proven that with this simple structure, not only the alignment can be done easily but also the aforementioned platform can be loaded with a heliostat of a few hundred kilograms without losing rigidity.

The next optical alignment procedure is to align the slave mirrors. This procedure has two steps: overlapping the slave images with that of master mirror and reducing the residual aberration by fine-tuning.

Each slave mirror is equipped with offset screws for the convenience of optical alignment. When the heliostat was initially installed, all the slave mirrors were paper blocked. The optical

alignment was conducted in the field by opening each slave mirror, one by one, and adjusting the offset screws to superpose its image with that of master mirror. The process would not take a very long time. The alignment takes 2–3 min for each mirror only.

For each row and column, offset screws are also available to reduce the residual aberration. This adjustment will take some time. A video camera is used to capture the image and to store it in the computer with time recorded. The offset adjustment is then made using the offset screws according to these daily image recordings. This process will continue for a few days to achieve the minimum residual aberration (Chai, 1998).

The pointing stability has been observed for a long time using the video camera and computer set up. Although the backlash of the mechanical parts and effect of wind and rain have been compensated by the structurally closed-loop control using optical encoders, residual image movements still exist due to the imperfection of mechanical design and the error of the parameters, i.e., the orientation of the heliostat rotation axis, the distance from the heliostat to the target, the latitude of the location, etc. For the past years, great efforts have been made in improving the precision. A special simulation program has been used to analyse the image movement and related factors to aid the precision improvement. From our observation of the tracking error in the previous prototype, the position of the image central point was at 0.7 cm above the required position at 11:00 am; it shifted 0.5 cm vertically downward and stayed there at 11:15 am; and finally it was located at 0.3 cm below the required position from 1:51 pm to 4:30 pm. The measured uncertainty of the pointing precision is about 1 cm, which is well within the range of tolerance for most applications.

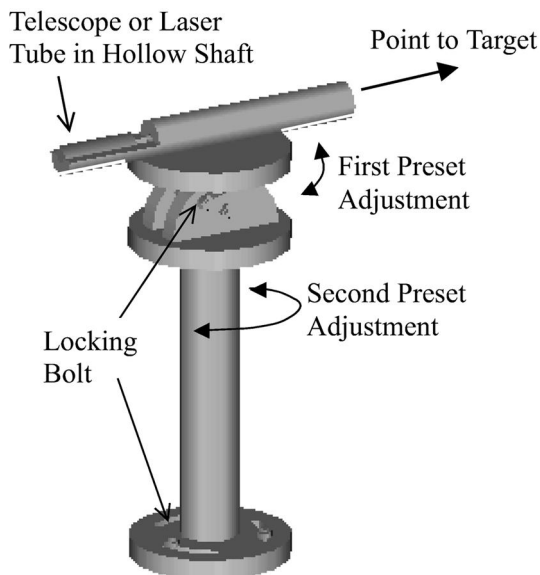


Fig. 8. Mechanical Design for the Optical Alignment of the Rotational Axis with the Target Plane. A laser tube or a telescope can be employed along the central axis of the shaft, which is mounted on a platform capable of two-degrees-of-freedom for optical alignment to the target.

4. DISCUSSION OF COST-EFFECTIVENESS

In the above, we have presented the principle of a new proposal for a solar collector and a prototype, which are different from currently used methods. One major problem obviously raised: whether this scheme is cost-effective comparing with current approaches. Of course it would not be fair to use the present prototype to make the calculation. The cost-effectiveness will be justified by more considerations as discussed in the following.

First, we shall consider the application aspect. Although our present prototype is at a small scale

because we need to prove the principle and to accumulate enough experience, the proposal was made aiming to a large scale or medium scale solar plant within the discriminating distance discussed in the above. For example, in principle, using the above-described principle and techniques, there is no problem to build a high temperature solar furnace of a few hundreds kW or higher. We believe a single stage solar furnace is obviously cheaper than a two-stage one. As a matter of fact, a 150 kW solar furnace is under construction using the present single stage scheme in UTM campus. It consists of 12 non-imaging focusing heliostats with a power tower at the centre.

We made an experiment to apply our prototype to supply power for a low power Stirling engine that may be just a match to the cost of a parabolic dish. However, the fixed target character of our present approach will allow a much higher power and heavier engine to be used because the engine will not need to move as in the case of a parabolic dish. According to our study in Malaysia, for the use of a remote community, a solar engine of 20–50 kW is most demanded. If such a Stirling engine can be built for usage under stationary conditions, it would be much less costly.

Secondly, we shall consider the designing aspect. The method we proposed requires some extra mechanisms to adjust the slave mirrors. This makes the design much more complicated than that of a conventional heliostat. Furthermore, the rotation-elevation tracking mode does not allow the centre of gravity of the heliostat frame to be in line with the supporting column. These two major problems bring a new challenge to the mechanical designers. The cost-effectiveness of the device will depend upon clever designs. In our research work, we found that the major obstacle for a simple and delicate mechanical design lies in the weight of the mirrors. Research work intensively goes on in this group to reduce the weight of the reflectors. Since our reflectors are relatively small, some previously tried or unpopular materials may find new use in our scheme. In our first generation prototype, a glass mirror was adopted. For a 4 m² collection area, the total heliostat weights 400 kg.

In our second generation prototype, an acrylic mirror was adopted. For a 16 m² collection area, the total heliostat weights also 400 kg. In order to further reduce the weight, we are studying the possibility of fabricating small membrane mirrors using materials like aluminum coil and other thin films such as Mylar etc. For that purpose, two of us (Y.T. Chen and B.H. Lim) are studying a new method to measure the reflectivity of mirrors at 10⁻³–10⁻⁴ level (relative measurement). This new method may provide a tool to study the life of alternative reflectors within a shorter time span.

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